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NASA'S SPACE LAUNCH SYSTEM: MOVING TOWARD THE LAUNCH PAD

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The National Aeronautics and Space Administration's (NASA's) Space Launch System (SLS) Program, managed at the Marshall Space Flight Center (MSFC), is making progress toward delivering a new capability for human space flight and scientific missions beyond Earth orbit. Designed with the goals of safety, affordability, and sustainability in mind, the SLS rocket will launch the Orion Multi-Purpose Crew Vehicle (MPCV), equipment, supplies, and major science missions for exploration and discovery. Supporting Orion's first autonomous flight to lunar orbit and back in 2017 and its first crewed flight in 2021, the SLS will evolve into the most powerful launch vehicle ever flown via an upgrade approach that will provide building blocks for future space exploration. NASA is working to deliver this new capability in an austere economic climate, a fact that has inspired the SLS team to find innovative solutions to the challenges of designing, developing, fielding, and operating the largest rocket in history. This paper will summarize the planned capabilities of the vehicle, the progress the SLS Program has made in the 2 years since the Agency formally announced its architecture in September 2011, the path it is following to reach the launch pad in 2017 and then to evolve the 70 metric ton (t) initial lift capability to 130-t lift capability after 2021. The paper will explain how, to meet the challenge of a flat funding curve, an architecture was chosen that combines the use and enhancement of legacy systems and technology with strategic new developments that will evolve the launch vehicle's capabilities. This approach reduces the time and cost of delivering the initial 70 t Block 1 vehicle, and reduces the number of parallel development investments required to deliver the evolved 130 t Block 2 vehicle. The paper will outline the milestones the program has already reached, from developmental milestones such as the manufacture of the first flight hardware, to life-cycle milestones such as the vehicle's Preliminary Design Review (PDR). The paper will also discuss the remaining challenges both in delivering the 70-t vehicle and in evolving its capabilities to the 130-t vehicle, and how NASA plans to accomplish these goals. As this paper will explain, SLS is making measurable progress toward becoming a global infrastructure asset for robotic and human scouts of all nations by harnessing business and technological innovations to deliver sustainable solutions for space exploration.

I. BACKGROUND

When the Space Shuttle Atlantis made its final landing at the Kennedy Space Center (KSC) in July 2011, retiring that productive low-Earth orbit capability after 30 years of service, NASA was already planning for a new launch vehicle to once again take human explorers beyond Earth orbit into deep space, while investing in private companies to help service the International Space Station market opened by the Shuttle and NASA's international partners (Fig. I).

The NASA Authorization Act of 2010 laid out the requirements for a powerful, versatile transportation system that could support a range of strategically important missions, such as the first Mars sample return on the course to eventual human journeys to explore another planet. NASA enlisted aerospace experts and stakeholders to participate in numerous studies that led to the Agency's selection of the SLS architecture in September 2011. Results of those trade studies are detailed in the "Preliminary Report Regarding NASA's Space Launch System and Multi-Purpose

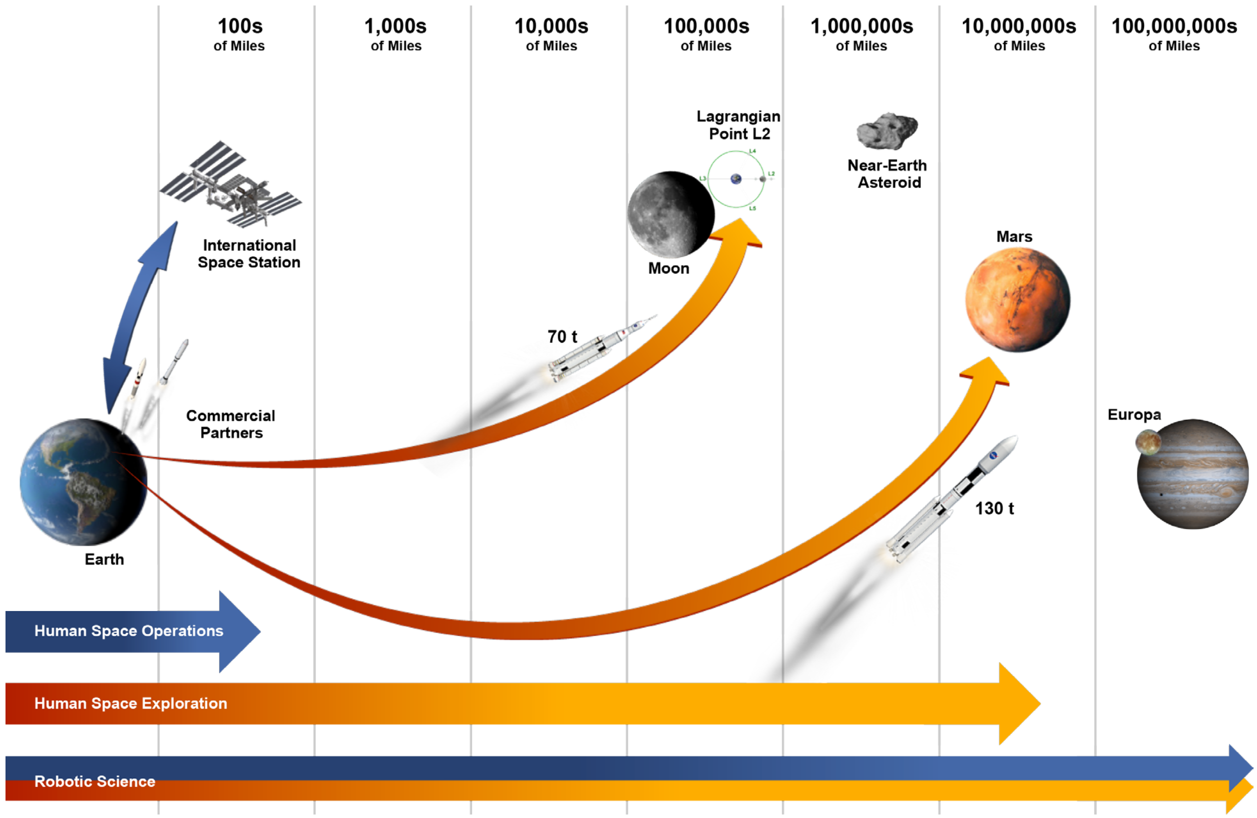


Fig. I: SLS value proposition for deep-space missions.

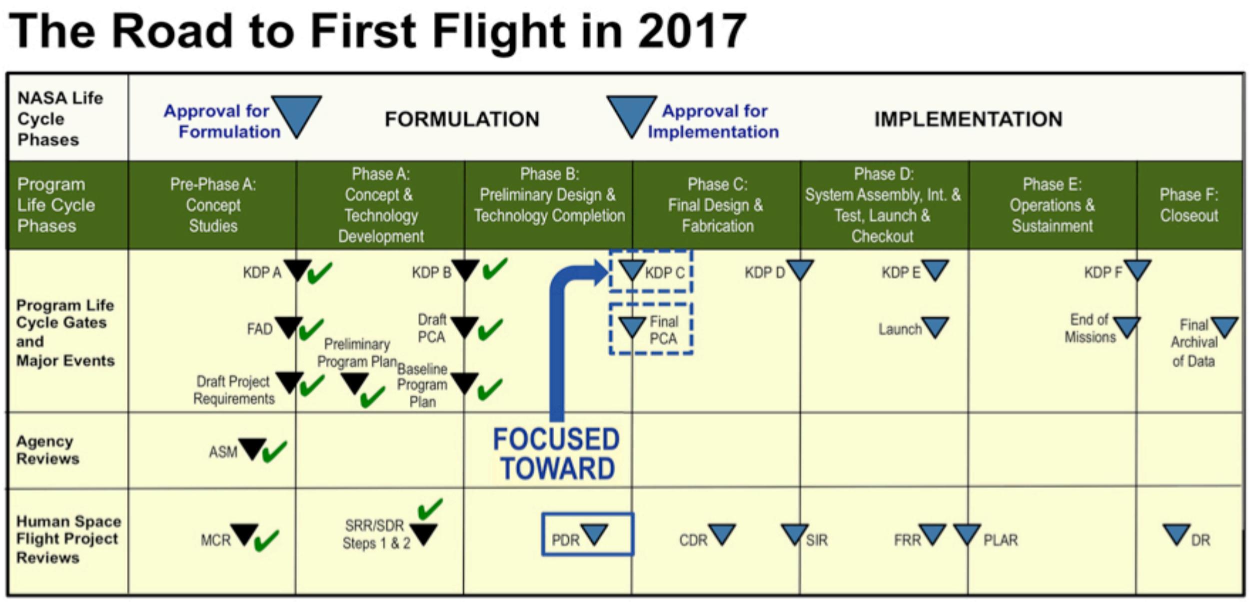
Crew Vehicle Pursuant to Section 309 of the NASA Authorization Act of 2010 (P.L. 111-267)." [1]

Based on requirements for a safe, affordable, and sustainable capability, the architecture selected is the best choice from among hundreds of concepts analyzed. A series of detailed trade studies was performed against numerous figures of merit with a common set of goals that included minimizing life-cycle costs, enabling challenging missions to deep space, and maintaining critical skills and transitioning the workforce effectively. From these concepts, three families of vehicles were chosen for further analysis including: (1) a liquid oxygen/liquid hydrogen (LOX/LH2) Shuttle-derived vehicle, (2) a liquid oxygen/hydrocarbon (LOX/RP-1) vehicle similar to the Saturn V, and (3) a modular core vehicle utilizing commercially-available assets. In addition, NASA released a Broad Agency Announcement that sought technical solutions to support heavy-lift system concepts and architectures and to identify propulsion technology gaps to support NASA's goals.

The three vehicle concepts were presented during an Agency-led Mission Concept Review in March 2011 (Fig. II), with senior manager Tom Gavin of the Jet Propulsion Laboratory serving as the Chair of the independent Standing Review Board commissioned to assist in this important decision. Former Space Shuttle flight director Leroy Cain followed Mr. Gavin as the Chair of the Standing Review Board for the SLS System Requirements Review and System Definition Review in July 2012, and the PDR in July 2013, as discussed below.

In parallel with these early studies, NASA's Procurement Office assessed the vehicle concepts from a fiscal perspective. This included the design, development, testing, and evaluation (DDT&E) investments

[1] "Preliminary Report Regarding NASA's Space Launch System and Multi-Purpose Crew Vehicle Pursuant to Section 309 of the NASA Authorization Act of 2010 (P.L. 111-267), http://www.nasa.gov/pdf/510449main_SLS_MPCV_90-day_Report.pdf



CDR: Critical Design Review	MCR: Mission Concept Review
EM: Exploration Mission	PCA: Program Commitment Agreement
EFT: Exploration Flight Test	PDR: Preliminary Design Review
FRR: Flight Readiness Review	SIR: System Integration Review
KDP: Key Decision Point	SDR: System Definition Review
Source: NPR 7210.5	SRR: System Requirements Review

Fig. II: SLS milestone schedule.

needed, as well as the nonrecurring operations costs expected. The Shuttle-derived design was found to offer the safest, most capable transportation system in the shortest amount of time for the anticipated near-term and long-range budgets, and the SLS plan of action reflects this storied heritage.

Over the last 2 years, the SLS team has matured the launch vehicle from concept to design in only 21 months. While operating within a constrained budget, the Program has effectively managed resources and finished each year with a positive balance sheet. The SLS Program's comprehensive progress attests to the Agency's commitment to provide a world-class launch vehicle that will take explorers and scientific spacecraft to deep space beginning later this decade. Following is a summary of the approach to delivering initial and evolved capabilities, along with brief hardware status reports.

II. INITIAL AND EVOLVED CAPABILITIES

The discussion of SLS progress and challenges is set against the backdrop of a robust launch vehicle that will deliver unsurpassed capabilities for entirely new missions in the near term and will evolve to even greater performance as resources permit (Fig. III). The SLS rocket will be the first to send astronauts beyond Earth's orbit since the Apollo Program in the 1970s and supports a number of potential payloads.[2]

The initial 70-t capability is achieving near-term goals by using proven heritage hardware and harnessing the unique U.S. aerospace infrastructure and experienced workforce to make rapid progress. Later, the design will be evolved to 130 t (Fig. IV) to handle the heavy lifting required for ambitious futuristic pursuits, as outlined in the NASA publication "Voyages: Charting the Course for Sustainable Human Space Exploration" and "The Global Exploration Roadmap." [3, 4]

[2] "Game Changing: NASA's Space Launch System Science Mission Design," paper presented at the IEEE Aerospace Conference 2013, March 2013, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013034_2013012810.pdf

[3] "Voyages: Charting the Course for Sustainable Human Space Exploration," June 2012, http://www.nasa.gov/exploration/whyweexplore/voyages-report.html#.UhZwPOBcTh4

[4] "The Global Exploration Roadmap," August 2013, http://www.nasa.gov/content/just-released-updates-to-the-global-exploration-roadmap/#.UhZxR-BcTh4

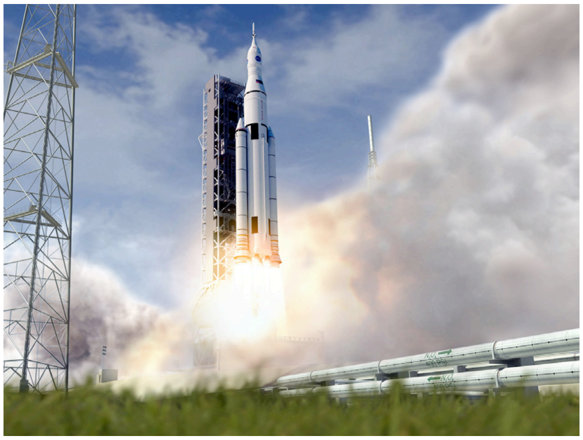


Fig. III: Artist's concept of SLS launching from the Kennedy Space Center.

By using common design elements, the SLS connections with the ground systems at KSC and with the spacecraft and payloads it carries will remain consistent over time, reducing complexity. The SLS operational scheme takes advantage of resources established for the Space Shuttle, including the workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and LOX/LH2 propellants.

With hardware arriving at KSC for launch processing beginning in 2016, the SLS vehicle will be prepared for its maiden voyage slated for December 2017 (Fig. V). The KSC launch complex is being readied for SLS operations and the contract to modify the mobile launch platform has been awarded.[5] The first mission will launch Orion on an autonomous flight to the Moon and back. In 2021, SLS will launch Orion with a crew aboard on a mission beyond the Moon, farther in space than humans have ever gone before. Future missions will include destinations such as Mars.[6]

The most costly part of any rocket development is its propulsion systems. The SLS design takes advantage of 16 Space Shuttle Main Engines (RS-25) in stock at the conclusion of the Space Shuttle era, leveraging a proven asset and maximizing the significant value of NASA's inventory. The SLS architecture also includes two 5-segement solid rocket boosters (SRBs), which were in development for the Constellation Program's Ares Project and are derivatives of the Space Shuttle's 4-segment SRBs. Continuing the contract already in place proved a significant cost avoidance and allowed a quick start to the design of the world's most powerful boosters. The Interim Cryogenic Propulsion Stage (ICPS) that will propel Orion to the far side of the Moon is a modified Delta IV Cryogenic Second Stage (DCSS), leveraging a valuable asset from the U.S. evolved expendable launch vehicle fleet.

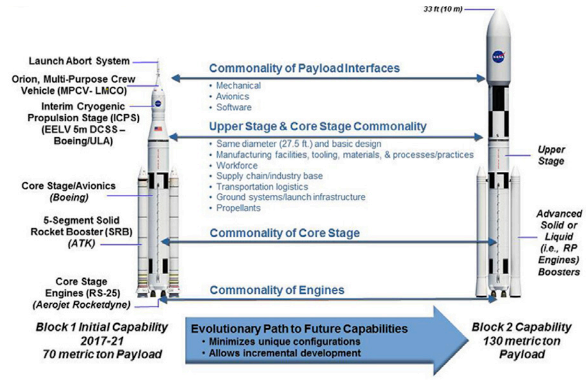


Fig. IV: SLS evolution path.

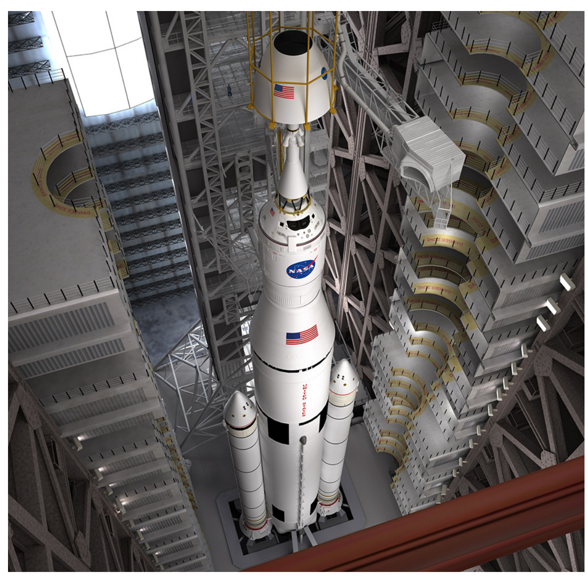


Fig. V: Artist's concept of SLS and Orion in the KSC Vehicle Assembly Building.

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[5] "NASA Awards Contract to Modify Mobile Launcher," Contract Release: C13-023, www.nasa.gov

[6] "U.S. has not abandoned Mars Sample Return," Frank Morring, Jr., Aviation Week, May 27, 2013, http://www.aviation week.com/Article.aspx?id=/article-xml/AW_05_27_2013_p20-580722.xml

The major new SLS hardware development is the massive core stage, which forms the vehicle's structural backbone and houses the LOX/LH2 tanks, as well as holds the instrument ring that contains vehicle-level avionics, which are based on commercially available software. The 8.4-meter (m) diameter stage is the same width as the Space Shuttle's external tank, taking advantage of the one-of-a-kind Michoud Assembly Facility (MAF) manufacturing infrastructure.

The 70-t vehicle will have 10 percent more thrust than the Saturn V at liftoff and the 130-t vehicle will have 20 percent more thrust with the addition of as-yet-to-be-determined advanced boosters and a cryogenic propulsion stage. As the vehicle is evolved to greater lift and larger fairing sizes, from 8.4 m to 10 m, the capacity that the SLS offers can reduce spacecraft design complexity. It can transport more equipment and cargo to distant destinations in less time, further reducing cost and risk for potential payload providers.

Measurable progress has been made for both the initial and evolved designs, with parallel trade studies being conducted for future advanced boosters and low-level investments being made in promising research and development, such as additive manufacturing, so that decisions made for the 70-t vehicle directly support the evolvability path to Mars and beyond.

III. PROGRESS REPORT

The SLS initiative pushes the boundaries of numerous clean-sheet developments that have come before. The SLS development schedule is planned to be 7 years instead of the 10 years it took to develop the Saturn V and Space Shuttle, primarily due to the use of heritage hardware. The development cost is projected to be a fraction of those programs and the vehicle is being designed to operate at much lower costs, as well.

The programmatic aspects of schedule and budget are key variables in solving the technical issues that normally occur when conducting an engineering feat of this magnitude. Learning the lessons of their forbearers while adopting modern methods such as value stream mapping, the SLS team's advantage includes everything from harnessing rich databases created over the last 5 decades, to applying judicious risk-based insight/oversight of contractor work. Taken together, the time and cost savings of each improvement are significant.

Tangible progress has been made on every aspect of the rocket. The first SLS flight hardware, which is being built today, is the Multi-Purpose Crew Vehicle (MPCV) Stage Adapter (MSA), a structural ring (Fig. VI) that will mate an Orion test article to a Delta IV rocket for a high-Earth orbit test flight in 2014.[7] Reflecting the SLS Program's "design once, build many times" affordability tenet, this same design will be used for full-up SLS missions, as well.

From accomplishments across laboratories, manufacturing facilities, and test stands, to disciplined resource management in an austere budget climate, the SLS Program is consistently meeting its commitments and steadily progressing toward delivery of a rocket for entirely new missions of global importance. The various hardware elements converge under the auspices of the systems engineering and integration (SE&I) function, which manages vehicle-level requirements and provides decomposed requirements to the elements; orchestrates myriad technical tasks to a predetermined timeline; and creates a climate that

Fig. VI: Stage adapter fit-check at Marshall Space Flight Center, June 2013.

[7] Adapter Flips for Progress Toward 2014 Exploration Flight Test, May 22, 2013, http://www.nasa.gov/exploration/systems/sls/ringflip.html

embraces healthy change tempered with experience and anchored by firsthand knowledge of space transportation systems.

Systems Engineering and Integration

The partnership between the programmatic and engineering functions ensures that the initial 70-t vehicle meets its performance requirements and is delivered on time and within budget at an acceptable risk level. The partnership also works to ensure that the evolved 130-t vehicle can be achieved with the least amount of development work and minimal configuration changes (reference Figure IV). In this arrangement, the SLS Program Manager is responsible for the programmatic baseline and the SLS Chief Engineer is responsible for the technical baseline. The technical baseline includes such aspects as the outer mold line and concept of operations, as well as factors such as mass properties, configuration-controlled design drawings, and so forth.

To that end, the SLS Chief Engineer manages the SE&I team, which is a lean organization comprising lead system engineers, discipline lead engineers, and a chief engineers network embedded within the vehicle elements (boosters, main engines, core stage/avionics, and spacecraft integration). SE&I personnel focus on the technical interfaces — structural, electrical, and organizational — between the individually procured hardware elements discussed below. This team performs vehicle-level analyses that are supported by a range of tools and analysis methodologies, such as wind tunnel flights and scale-model acoustic testing, among others (Fig. VII). [8, 9]

The SLS SE&I team began with requirements analysis cycles, which helped define the optimum architecture, and then matured to design analysis cycles to calibrate the individual elements and determine that the system will deliver the performance expected. The SE&I integrated master schedule provides interdependencies and deliverables, shows work durations, and identifies which data products feed which programmatic milestones. Using the classic systems engineering "V", which represents validation on the downward slope and verification on the upward side, some of the activities and associated products are serial in nature, while others progress simultaneously. Following the third design analysis cycle, which is now in progress, a verification analysis cycle will begin, using variables such as the results of trade studies at the vehicle and element levels, modeling and simulation of mission scenarios, and a range of increasingly flight-like testing to refine the architecture leading up to the SLS Critical Design Review (CDR) in 2015.

Fig. VII: KSC water suppression system design scale model acoustic testing at MSFC.

While competitive opportunities have been made available for affordability on-ramps as the vehicle is evolved, the initial SLS design makes maximum use of existing assets, infrastructure, and workforce — all factors that contribute to affordability. As stated earlier, the extensive use of heritage hardware in the SLS design presents both opportunities and challenges. Using existing contract mechanisms provided a quick start and a specific scope of work. This approach maintained forward progress during policy changes and budget refinements. It also reduces the technical, cost, and schedule risk inherent in new developments.

While heritage hardware comes with well-known characteristics, it also brings with it challenges relative to using technology designed for a specific application being used in new environments. Some of these are covered in the element sections below, along with sample solutions under consideration. The SLS Chief Engineer conducted a technical panel on this topic at the American Institute of Aeronautics and Astronautics 2013 Joint Propulsion Conference, and

[8] SLS Model Flight Through Langley Wind Tunnel Testing, Nov 28, 2012, http://www.nasa.gov/exploration/systems/sls/sls_windtunnel.html

[9] Sale Model Acoustic Testing for Space Launch System, 2013, http://www.nasa.gov/exploration/systems/sls/multimedia/gallery/smat1.html

the available technical literature covers many of the decisions being made to integrate the vehicle in the most optimum way.[10,11]

5-Segment Solid Rocket Boosters

The 5-segment SRBs for the first two SLS flights are produced by Alliant Techsystems, Inc. (ATK) and will be the most powerful in the world, delivering 3.55 million pounds of thrust during the early boost phase of flight. Heritage hardware and design includes forward structures, metal cases, aft skirt, and thrust vector control. The upgraded hardware and expendable design includes the solid rocket motor, avionics, and asbestos-free insulation.

Among the challenges of applying heritage hardware to the new SLS configuration has been with the forward separation bolt. This bolt is part of the system required to actively detach boosters from the main vehicle upon completion of booster firing. Two features will be improved. First, the bolt will be made stronger to accommodate the higher loads on the bolt as the booster thrust decreases and the core continues to accelerate. To handle this, the separation bolt groove will be shallower, which gives the bolt a larger cross-sectional area and makes the bolt stronger. Exact depth of the groove will vary from each lot of bolt material and will not be determined until the material properties from the lot of material have been determined. A second improvement will be to change the tolerance band for the pressure cartridge. The minimum charge allowed will be changed to help guarantee that the pyrotechnics in the cartridge will be the right amount to break the stronger bolt.

Fig. VIII: QM-1 center aft segment at ATK's test area, May 2013.

Following three successful developmental motor tests, the first qualification motor (QM-1) is now being manufactured (Fig. VIII). Following the QM-1 test in 2014, the instrumented motor will be disassembled and inspected prior to casting QM-2 segments. QM-2 testing is scheduled for 2015. Following disassembly, inspection, and analysis of QM-2, decision gates will lead to booster fabrication for Exploration Mission 1 (EM-1).[12]

Booster avionics boxes control the stage, take measurements, and communicate with the vehicle using an ignition separation controller, hydraulic power unit controller, booster control power distribution unit, and actuator control unit. Demonstration tests and flight control tests have been conducted to support QM-1 and -2 full-scale static tests.[13] In addition to contractor facilities, an avionics hardware-in-the-loop facility at MSFC allows end-to-end control system testing under simulated load conditions for development and certification testing.

In 2012, the Booster Element Office conducted extensive value stream mapping processes, which helped gain efficiencies and improvements by reducing hardware moves and eliminating unnecessary requirements by up to 40 percent throughout the manufacture and assembly process at ATK facilities. The SLS Booster Office completed its PDR in April 2013 and is scheduled for its CDR in 2014. The booster flight set is slated for delivery to KSC for processing in mid-2017.

RS-25 Main Engines

The RS-25 main engine delivers more than 500,000 pounds of thrust at 109 percent rated power level.

[10] Guy Norris, "Heavy Lifter: SLS development coming together as launch and ascent loads come into sharper focus," Aviation Week and Space Technology, July 29, 2013.

[11] Guy Norris, "Loads Challenges Remain for SLS Design," Aviation Week and Space Technology, July 29, 2013.

[12] Chris Bergen, "Full Steam Ahead for ATK's SLS Booster Drive," May 4, 2013, http://www.nasaspaceflight.com/2013/05/full-steam-ahead-atk-sls-booster-drive/

[13] "Flight Control Test 2 at ATK," January 2013, http://www.nasa.gov/exploration/systems/sls/multimedia/gallery/fct_test_1.html

Produced by Aerojet Rocketdyne, the RS-25 is the first reusable rocket engine in history, as well as the most reliable and highly tested large rocket engine ever built. During the 30-year Space Shuttle era, the RS-25 achieved 100 percent mission success with a demonstrated reliability exceeding 0.9996. During 135 missions and related engine testing, the RS-25 system accumulated over 1 million seconds of hot-fire experience. Whereas the Shuttle flew a 3-engine configuration, the 70-t SLS will fly with 4 engines. The SLS has 16 engines in its inventory at the Stennis Space Center (SSC), enough for its first 4 missions.

At 100 m, the SLS is 42 m taller than the Shuttle, which results in higher LOX propellant inlet pressures in the engine, a challenge that is being worked from at least three angles: (1) slightly modifying the engine to adapt to expected pressures, (2) limiting maximum pressure within mission profile changes through throttling, and (3) modifying the start sequence. The larger SLS core stage will result in lower LOX temperatures, which have the potential to damage the engine induced by temperature spikes during the start sequence. After investigating several solutions, reducing pre-start bleed flows and modifying the start sequence, along with the use of lightweight, low-wattage heaters to warm the LOX before it enters the engine, are expected to solve this challenge with the least amount of impact.

Since the RS-25 production concluded several years ago and the vendor and supplier chain has changed, the SLS Engines Element Office has done innovative research to prepare for future cost-effective engine production. One of these research areas is additive manufacturing, also known as three-dimensional (3-D) printing, which is reducing the time to manufacture certain parts from months to days, thereby reducing production costs to a fraction of their former expense. Another benefit is that quality can be improved by making a homogenous part with no welds. Parts manufactured to date include the hot gas duct and turbine housing cover, both with excellent results during J-2X hot-fire testing (Fig. IX).[14, 15]

Fig. IX: J-2X testing firing with 3-D printed part, June 2013.

The J-2X engine development started under the Constellation Program has also resulted in a new common engine controller that is being adapted for use by the RS-25, resulting in cost savings.[16] The engine controller allows the vehicle and the engine to communicate, sending commands down to the engine and transmitting data back to the vehicle. The controller also provides closed-loop management of the engine by regulating thrust and the fuel mixture ratio while monitoring the engine's health and status. This technology provides a modern foundation for functions such as throttling the engine — allowing it to fly in ways that minimize the loads that result from producing 10 percent more thrust than the Saturn V Moon rocket.

NASA plans to begin testing RS-25 engines in 2014. The J-2X equipment installed on the A-1 Test Stand could not be used to test RS-25 engines since it does not match the engine specifications and thrust requirements, namely the J-2X engine produces 294,000 pounds of thrust and the RS-25 engine produces over 500,000 pounds of thrust. Fabrication recently began at SSC on a new thrust frame adapter for the A-1 Test Stand to enable this testing. This will be followed by core stage/main engine green run testing in 2016 on the B-2 Test Stand at SSC; refurbishments are now in progress. The Engines Office completed its PDR in April 2013.

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[14] Space Launch System Providing Engine "Brains" with an Upgrade, October 17, 2012, http://www.nasa.gov/exploration/systems/sls/rs25_engine.html

[15] Hot-Fire Tests Show 3-D Printed Rocket Parts Rival Traditionally Manufactured Parts, July 24, 2013, http://www.nasa.gov/exploration/systems/sls/3dprinting.html#.UhYyuuBcTgA

[16] Future of Exploration Stars with 3-D Printing, http://www.nasa.gov/exploration/systems/sls/j2x/3d_print.html#.UhYzfuBcTgA

Core Stage

The core stage is the only major new development in the SLS acquisition plan. The massive 8.4-m-diameter, 61-m-tall tank that forms the rocket's structural backbone is being built by the Boeing Company at MAF, where the Saturn stages and Shuttle external tanks were manufactured. The stage, made of Aluminum 2219, will hold the 4 RS-25 main engines and LOX/LH2 propellants.

Following a steady cadence of installing 6 substantial welding tools in MAF, the first LH2 tank barrel segment was completed in July 2013 (Fig. X). It is considered a "confidence" barrel segment because it validates the vertical weld center (VWC) is working the way it should. The VWC is a friction-stir-weld tool for wet and dry structures on the SLS core stage.[17] Completed in June, the VWC will weld barrel panels together to produce whole barrels for the core stage's 2 pressurized tanks, the forward skirt, and the aft engine section. The massive machine stands 3 stories tall and weighs 136,000 kilograms (kg). The finished barrel segment is 6.7-m tall and weighs 4,100 kg. The segment will be used in structural tests to ensure the integrity of the piece. Five similar barrels and 2 end domes will be constructed to make up the SLS core stage LH2 tank.

Fig. X: First LH2 tank confidence barrel section welded at MAF, July 2013.

[17] "First Liquid Hydrogen Tank Barrel Segment for the SLS Core Stage Completed at Michoud," http://www.nasa.gov/exploration/systems/sls/sls-barrel-at-michoud.html#.UfqSkeBcTga

The core stage also contains the instrument ring, which houses the vehicle-level avionics. The flight computers are currently in testing at the MSFC Software Development Facility in an effort to rapidly mature and ensure implementation of a safe and highly reliable avionics and software system. Following this testing, the software will be installed and tested in the System Integration Test Facility, also at MSFC. These facilities allow technicians to "fly" the vehicle through virtual space and make adjustments accordingly.

Currently, over 200 design drawings are being released per month. The core stage PDR was completed in December 2012, 5 months ahead of schedule. The core stage CDR is slated for mid-2014. All avionics components have completed their PDRs, with some having completed CDR. In 2015, the avionics will be shipped to MAF for integration into the stage, where the RS-25 engines will also be integrated. The integrated stage is due to be delivered to KSC for launch processing in late 2016/early 2017.

Spacecraft and Payload Integration

As shown in the expanded view below (Fig. XI), the Spacecraft and Payload Integration Office (SPIO) manages three areas: (1) the MSA, discussed above, which will connect the Orion MPCV to the upper stage (refer to Fig. VII); (2) the launch vehicle stage adapter (LVSA), which will attach the mated upper stage and Orion to the rocket; and (3) the ICPS upper stage (Figure XII). In addition, this office has been performing conceptual analyses of payload fairings to support SLS evolvability studies. The MSA is an in-house development for the Exploration Flight Test in 2014, and will be delivered to KSC for processing in

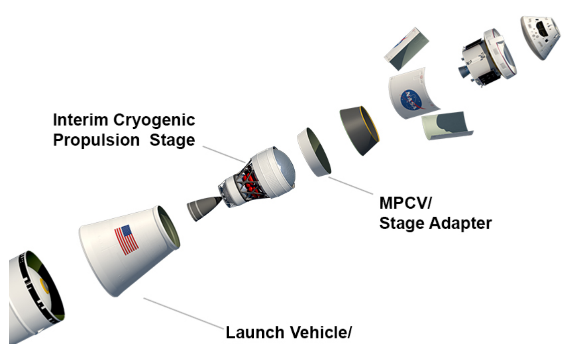

Fig. XI: Expanded view.

Fig. XII: Artist's concept of the ICPS with Orion in orbit.

late 2013. Also in late 2013, the LVSA will be competitively procured.[18] SPIO completed its PDR in June 2013.

The Delta IV cryogenic second stage (DCSS) has completed over 20 flights; however, this heritage hardware is being modified to the ICPS to perform the SLS mission, including stretching the tank to hold the propellants needed to send Orion to lunar orbit. The RL10B-2 engine was rated for a certain set of loads and environments, so analyses are in progress to determine other modifications that might be needed to handle the higher performance of the SLS. Specifically, the lateral loads imparted at liftoff due to winds at the launch pad and the ascent loads generated by aerodynamic buffeting exceed those of the DCSS environments for which the original hardware was designed. Mitigations include a T-zero stabilizer liftoff restraint and release system at the launch pad, as well as system damping. For ascent, additional analyses are being conducted to determine the optimum solution such as active electromechanical actuators in the thrust vector control system that will adjust to the predicted aerodynamic environment. Using heritage and commercial hardware ultimately saves time and money, but comes with a set of engineering challenges and programmatic risks that must be managed to achieve the desired results.

IV. CONCLUSION

NASA strives to deliver maximum value for the U.S. investment in space. To determine that its large-scale initiatives are technically and fiscally sound, the Agency conducts stringent engineering and business evaluations to gauge progress and reduce the risk of doing things that have never been done before. The SLS Program and its elements have successfully completed their Preliminary Design Reviews, during which progress was checked against rigorous engineering standards and well-defined management practices (refer to Fig. II). The next life-cycle milestone will be the Critical Design Review, slated for 2015, further affirming that technical work is sound and management planning is sufficient to proceed to hardware manufacturing and testing on the road to vehicle integration and first flight in 2017 (Fig. XIII).

For demanding space missions, transportation solutions must be robust. While the SLS team is focused on delivering the initial 70-t launch capability, the vehicle is evolvable through selected hardware upgrades and developments into a 130-t rocket that will be the largest ever built. The SLS Program is making significant progress toward delivering a new transportation capability for deep-space missions that will expand territories for commerce, rewrite textbooks with new discoveries, and push the envelope of technologies with terrestrial applications. The SLS is a powerful enterprise asset that will make possible these and other benefits for all Earth's people.

Fig. XIII: Artist's concept of the SLS at liftoff.

[18] Building the Stage Adapter for Orion and SLS, http://www.nasa.gov/exploration/systems/sls/multimedia/gallery/msa2.html

National Aeronautics and Space Administration

NASA's Space Launch System: *Moving Toward the Launch Pad*

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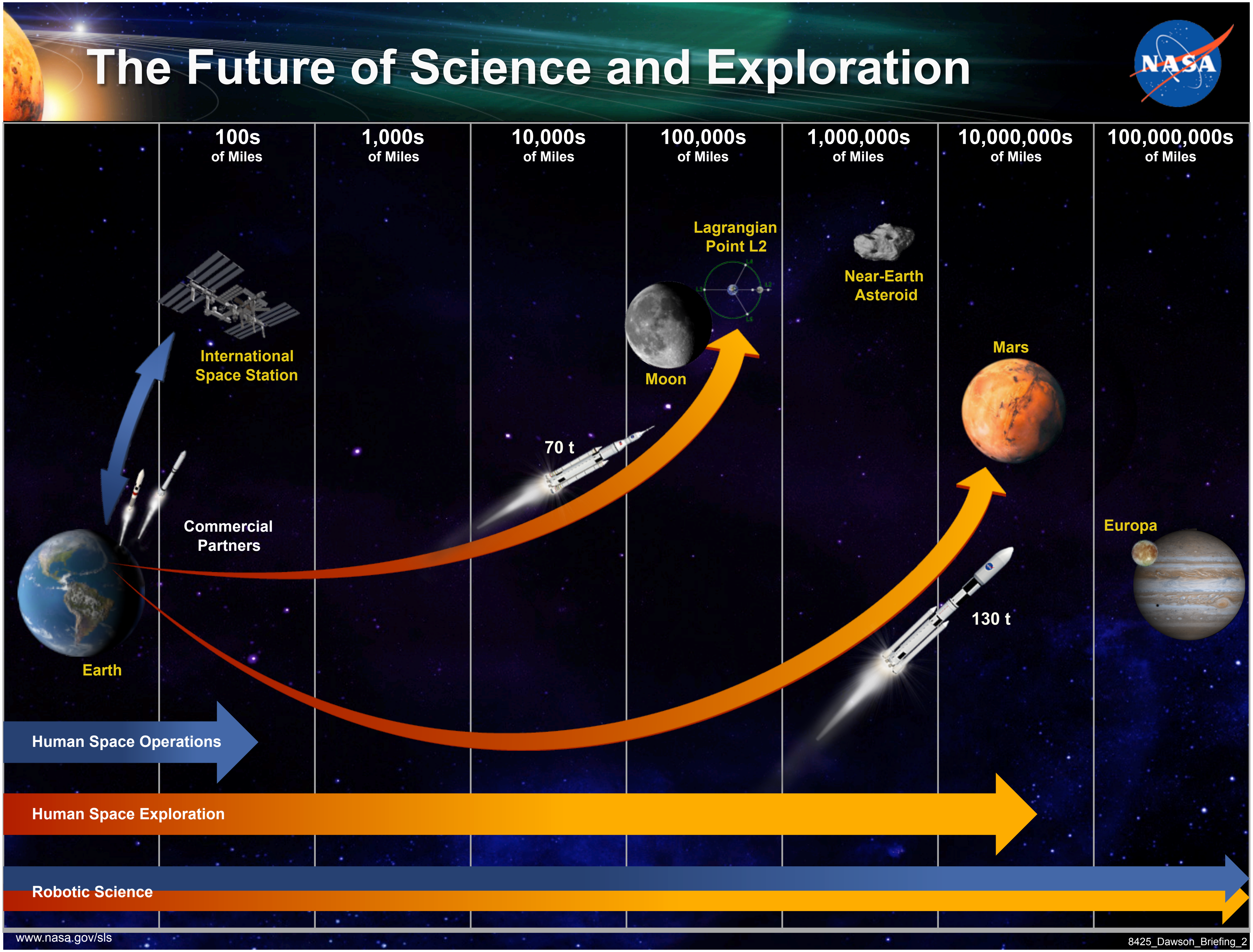
Space Launch System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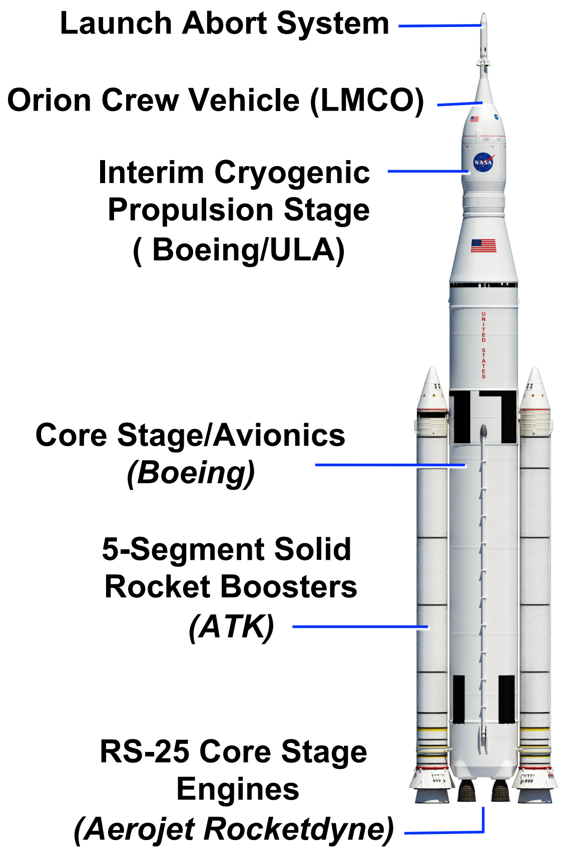
8425_Dawson_Briefing_2

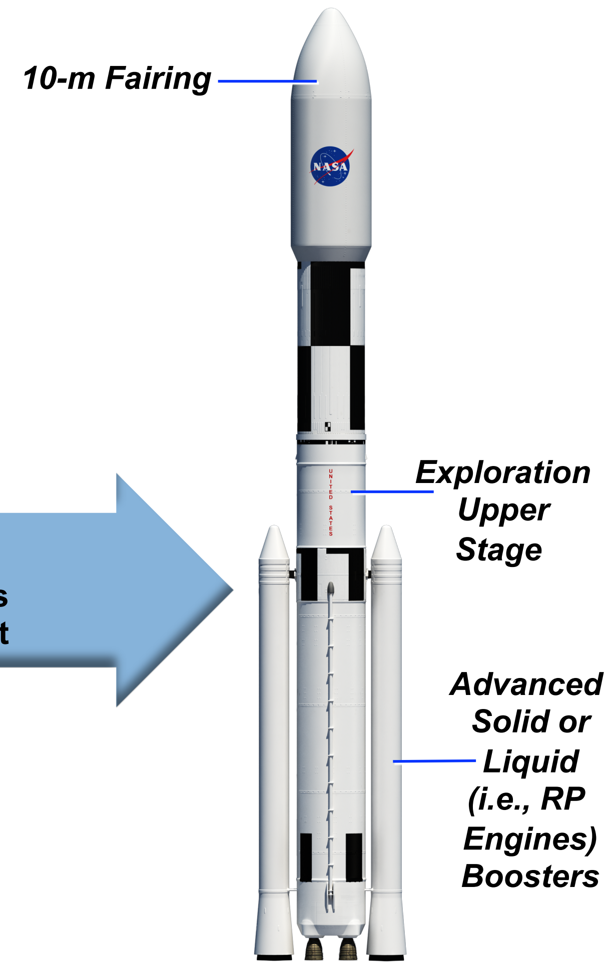
SLS Current and Future Capabilities



Block 1 Initial Capability
2017-21
70-t Payload

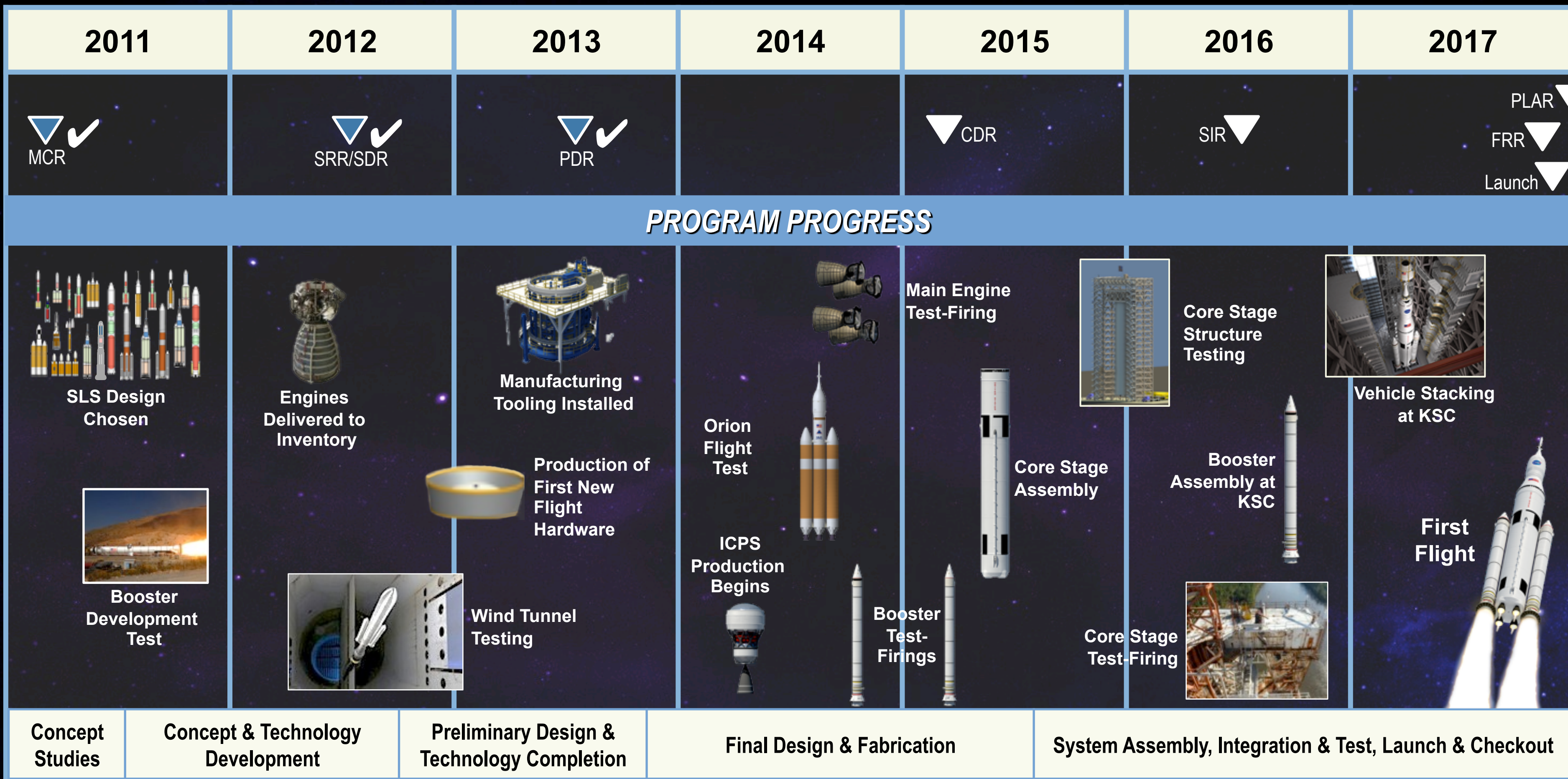
Evolutionary Path

- **Minimizes unique configurations**
- **Allows incremental development**



Block 2 Capability
130-t Payload

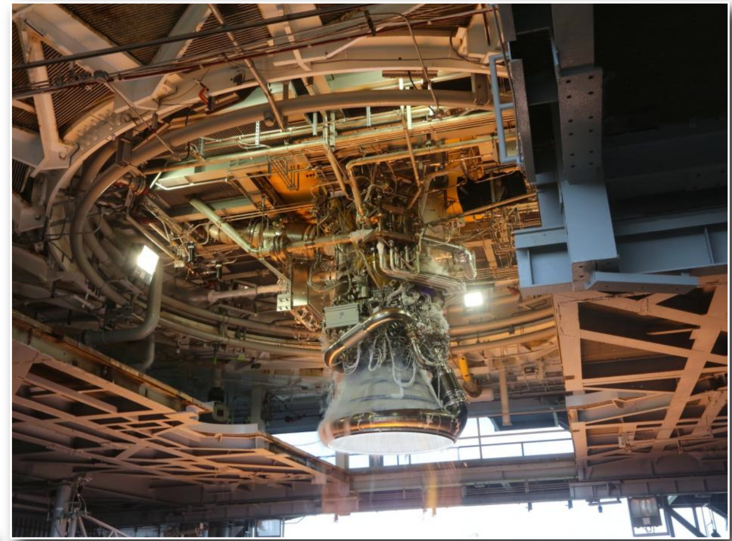
SLS Development Schedule



MCR: Mission Concept Review	CDR: Critical Design Review
SRR: System Requirements Review	SIR: System Integration Review
SDR: System Definition Review	FRR: Flight Readiness Review
PDR: Preliminary Design Review	PLAR: Post-Launch Asses. Review

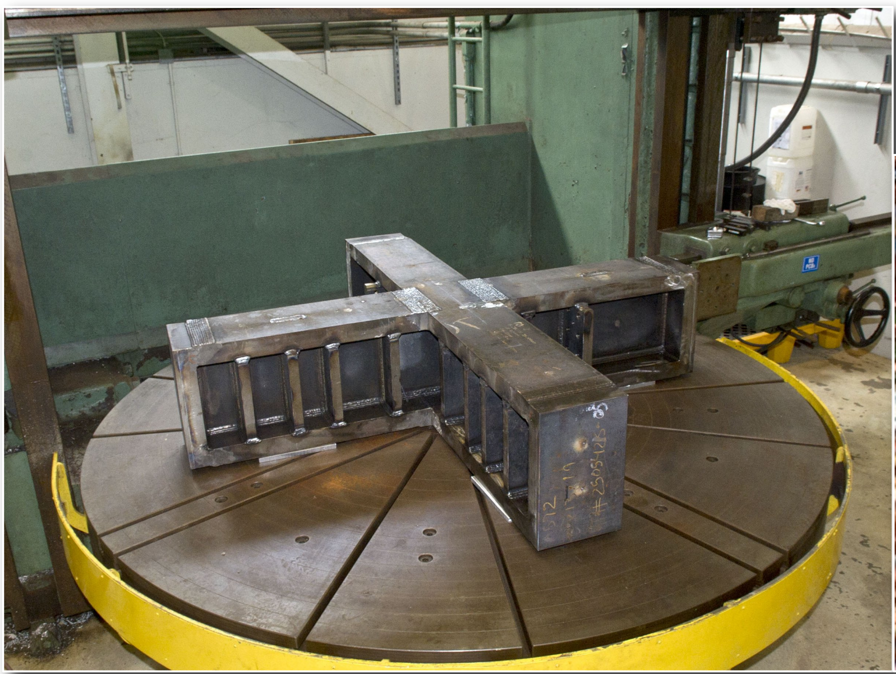
Engines Progress

RS-25 engines in inventory at Stennis Space Center (SSC) for first 4 flights



Gimbal testing of J-2X engine with selective laser melted (additive manufactured) component at SSC, June 2013

Production of thrust frame adapter for RS-25 testing on A-1 Test Stand at SSC, June 2013



B-2 Test Stand being prepared for green run testing at SSC, July 2013

Boosters Progress

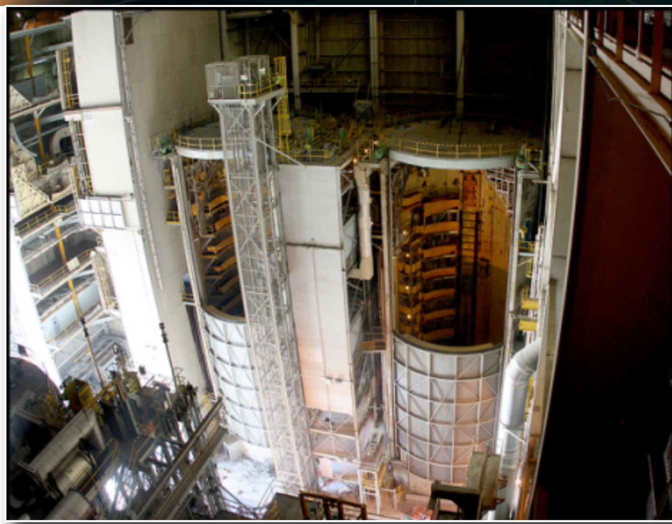
5-Segment Solid Rocket Motor Development Test 3 at ATK in Promontory, UT, September 2011

Qualification Motor casting 2012–2013

Center segment for Qualification Motor 1 delivered to Test Stand T-97 at ATK for test-firing in 2014

Flight Control Test 2 at ATK, January 2013

Stages and Avionics Progress



Michoud Assembly Facility (MAF) in New Orleans preparing for SLS Core Stage construction, June 2013

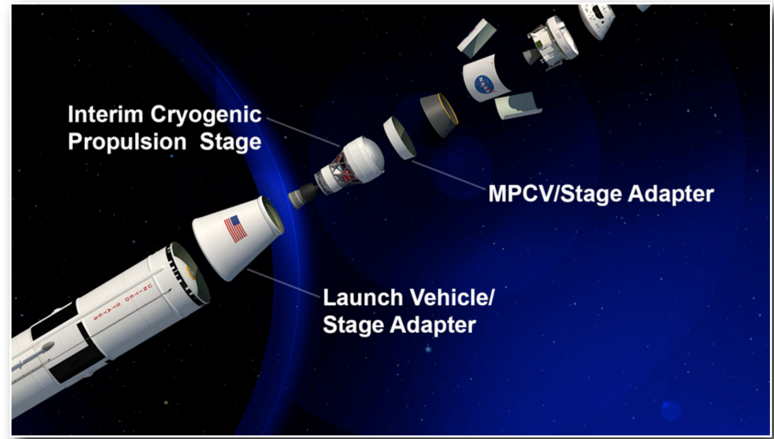
Avionics Software Test-Bed at Marshall Space Flight Center (MSFC), May 2012

First liquid hydrogen tank confidence barrel section welded at MAF, July 2013

Planning Adaptive Augmenting Control flight test at Dryden Flight Research Center, CA, June 2013

Spacecraft & Payload Integration Progress

Successful fit-check of Multi-Purpose Crew Vehicle Stage Adapter to Delta Cryogenic Second Stage at Marshall Space Flight Center, June 2013

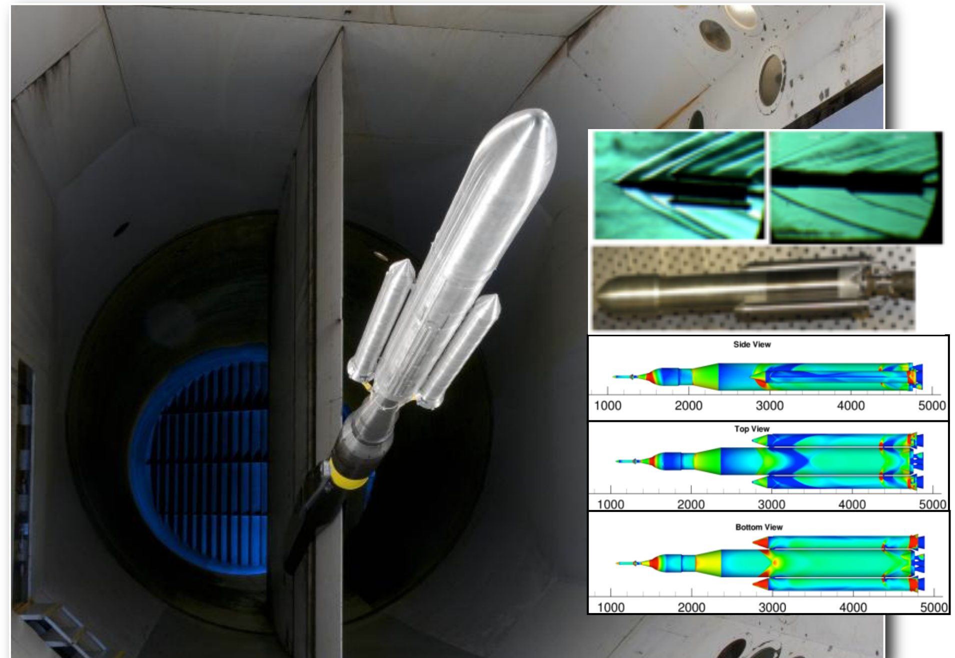


Launch Vehicle Stage Adapter

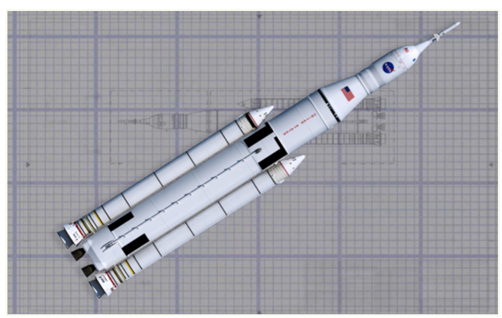
Interim Cryogenic Propulsion Stage

Systems Engineering & Integration Progress

Scale Model Acoustic Testing at MSFC to help design water suppression system for launch pad facility, April 2013



NASA's Space Launch System buffet model in NASA's Langley Research Center's Transonic Dynamics Tunnel, November 2012



Completed Preliminary Design Review, July 2013

International Platform for Deep-Space Missions